Abstract

Wearable antennas have emerged as a key enabling technology for body-centric wireless communication systems, driven by the increasing demand for unobtrusive, lightweight, and conformal devices. The integration of antennas with flexible materials allows for seamless incorporation into garments and accessories while ensuring mechanical resilience under dynamic body movements. The rapid advancement of the technologies has created a growing demand for wearable systems that support high-speed, low-latency, and energy-efficient wireless communication. This study focuses on the design and analysis of conformal, flexible, and low-profile wearable antennas. This report explores material selection, simulation analysis, fabrication techniques, and performance metrics essential for reliable wearable antenna systems for wireless communication. In addition to this it briefs about relevant considerations for designing and integrating the antenna into suitable materials, while maintaining optimal electromagnetic performance and user safety as per SAR limit for both the head and body mentioned in ICNIRP guidelines.

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List of Abbreviations

4G	Fourth Generation……1
5G	Fifth Generation……...1
6G	Sixth Generation……..……3
ARVR	Augmented Reality and Virtual Reality……...3
B5G	Beyond Fifth Generation……1
CST	Computer Simulation Technology……...9
dB	Decibel……..……...3
DM	Distributed Monopole……..2
DR	Dielectric Resonator……2
FR4	Flame Retardant 4……2
HFSS	High Frequency Structure Simulator……...9
ICNIRP	International Commission on Non-Ionizing Radiation Protection……..2
IoT	Internet of Things……..…..4
IR-UWB	Infrared-Ultrawideband……...5
ISM	Industrial, Scientific, and Medical……..4
MIMO	Multiple Input Multiple Output……...2
MSA	Microstrip antenna……...2
mmWave	Millimeter wave……..…….3
RF	Radio Frequency……..……3
RT	Rogers Trademark……2
SAR	Specific Absorption Rate……2
VNA	Vector Network Analyzer……..10
VSWR	Voltage Standing Wave Rstion……2
WBAN	Wireless Body Area Networks……4
Wi-Fi	Wireless Fidelity……..1

1. Title

Design a Novel Human Body Mounted Wideband Antenna Employing Flexible Material For Wireless Communication.

2. Aim of Study

The aim of the research work is to design and develop a novel, flexible wideband antenna using suitable material for wireless applications. In addition, the research work will focus on off-body and on-body performance characteristics of the antenna such as gain, bandwidth, radiation pattern, efficiency, polarization, bending , crumpling and trans-receiving capacity of the antenna.

3. Research Objectives (RO) of Study

RO1 To investigate the suitable antenna shapes and optimize its performance parameters such as gain, bandwidth, radiation pattern, efficiency, polarization and trans-receiving capacity for wireless applications.

RO2 To evaluate the impact of different flexible materials suitable for antennas used in wireless applications.

RO3 To conduct thorough experimental validation of antenna prototypes in realistic scenarios for wireless communication.

RO4 Design and simulation of novel antenna for various on-body applications and its performance testing in anechoic chamber as well as open environment.

RO5 To explore innovative techniques for antenna conformability and integration with wearable devices.

4. Study Background (Literature Review) and Significance of Study

Wireless communication involves transmitting information between devices without physical cables, utilizing radio waves, infrared, or other electromagnetic radiations. Common wireless technologies include Wi-Fi, Bluetooth, cellular networks for e.g. 4G, 5G, B5G, and satellite communication. B5G or 6G is the next revolution of wireless communication. An antenna plays an important role in establishing wireless communication. In [1-5] ,various parameters of the antenna

such as gain, impedance bandwidth (VSWR ≤ 2), radiation pattern, polarisation, efficiency, trans-receiving capacity between transmitter and receiver were discussed.

Wireless communication includes various types of antennas as depicted in Fig 4.1. Advancement of the various technologies has enabled the widespread adoption and functionality of various wireless applications. Various wireless applications involve wearable antennas. Antennas are made of rigid and flexible substrates. They are crucial components in modern wireless systems, enabling real-time data transmission and reception. Unlike traditional antennas, wearable antennas must address challenges such as body proximity effects, mechanical deformation, and specific absorption rate (SAR) compliance as per the ICNIRP guidelines. As wireless systems become more mobile and ubiquitous, the antenna design must align with the dynamic requirements of mobility, comfort, and integration with clothing or wearable electronics. Recent growth in wearable electronics and various technologies has necessitated the development of antennas that are lightweight, flexible, and body-compatible. Traditional antennas such as microstrip antennas (MSAs) made up of rigid substrate like FR4, RT Duroid etc. are not suitable for wearable devices or applications as they might undergo mechanical deformations. These antennas also suffer from performance degradation and it is not comfortable when worn close to the human body There is a shift in resonant frequency i.e. detuning due to change in impedance characteristics of antenna because of the body to body variation in tissue, bone density etc.

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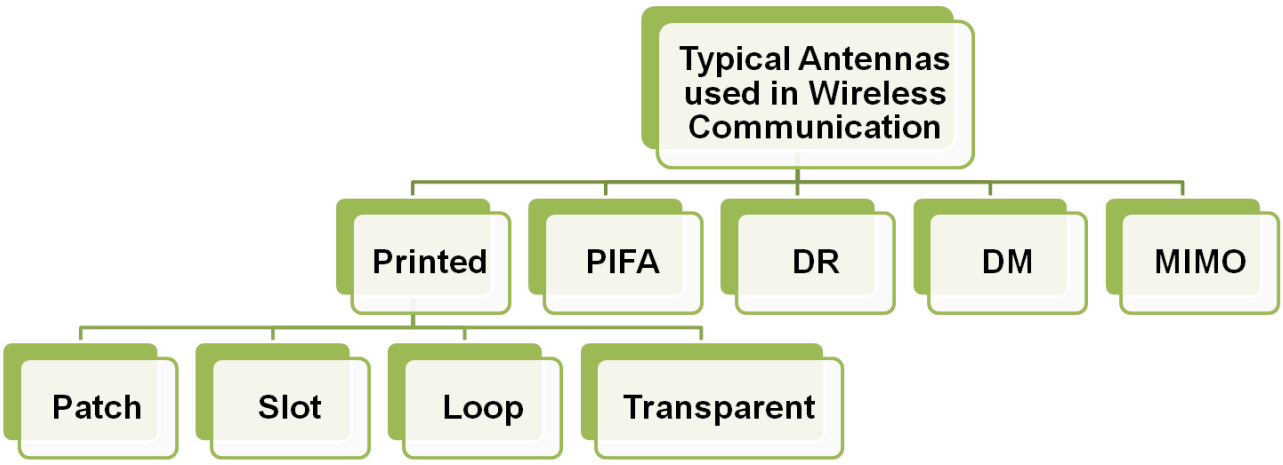

Fig 4.1 Antenna used in Wireless Communication

When any antenna is designed for on body wearable applications Specific absorption rate (SAR) value of the proposed antenna should be within the specified limit for head and body as per the

ICNIRP guidelines. In India, the SAR limit for both the head and body is 1.6 W/kg averaged over 1 gram of tissue, whereas in European countries it is 2 W/kg averaged over 10 grams of tissue. However, most existing designs lack comments on SAR values rather more focus is on data trans receiving capacities.

Development of a millimeter-wave (mmWave) wearable antenna operating at 24.15 GHz for virtual reality devices in [6] . The antenna features low-loss polyester fabric and a smooth coating to minimize dielectric and surface losses. Though with an S11 value of -29 dB, it ensures efficient interaction with VR systems, especially in low-light environments, few aspects like bandwidth can be dealt with to improve it from 0.1GHz to some effective increased value. In [7] wearable antennas were designed for cross-body communication in Virtual Reality applications. These antennas facilitate seamless data transmission between the user's body and Virtual Reality devices, enhancing user experience by reducing the need for external controllers. The work represented here includes probe feeding that can be replaced with strip feed or aperture feed to avoid damage. Grounding can be improvised to avoid loss due to reflection. A transparent antenna system suitable for Beyond 5G (B5G) and 6G networks was designed in [8]. These window-type and augmented reality glass-type antennas integrate seamlessly into everyday objects, enabling unobtrusive communication capabilities in next-generation networks. The work only highlights the applications like trans-receiving no focus on the antenna design parameters like substrate material, gain which are the key factors while designing for an ARVR device. In [9] an optically transparent antenna designed for smart glasses was explained. This antenna maintains aesthetic appeal while providing reliable communication, making it ideal for wearable devices that require both functionality and style. As per the review casing of the antenna can be compared for the enclosure loss reduction below 25%. In addition to it efficiency can be improved further by modifying the layering stack.

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In [10] Pantœnna, a system that estimates mouth pose using a low-profile antenna integrated into AR/VR headsets was discussed. By analyzing impedance characteristics, it captures facial expressions and speech without privacy concerns associated with camera-based methods, offering a robust solution for expressive avatars in virtual environments. It includes the application based description, Very less details available on antenna parameters. Substrate material is a Lossy copper material. We have a scope of exploring other flexible materials.. [11] introduces extended-AR, an AR system that extends perception beyond the line of sight using RF sensing. By integrating AR-conformal antennas and RF-visual localization algorithms into AR headsets like Microsoft

Hololens 2, extended-AR achieves decimeter-level localization of occluded objects, enhancing applications in manufacturing and warehousing. Current literature covers very poor negative gain values. There is a scope for size reduction and on-body testing for the performance improvement with positive gain value.

[12] introduces a broadband high-gain planar microstrip antenna designed for enhanced performance in wireless communication systems. The antenna's design emphasizes wide bandwidth and high gain, making it suitable for applications requiring robust signal reception and transmission. [13] presented modified triangular monopole antennas aimed at achieving wideband performance. These antennas are optimized for applications where broad frequency coverage is essential, such as in IoT systems. [14] explored the design and performance of compact wearable textile antennas tailored for IoT applications. Their study highlights the integration of antennas into textile materials, offering flexibility and comfort for users. It highlights only the narrow band spectrum and only one fabric (jean) was tested, In addition to that body effects were not adapted. [15] represents a wearable IoT-optimized textile antenna that operates across three frequency bands while maintaining a low Specific Absorption Rate (SAR). This design ensures user safety while providing efficient communication capabilities. [16] reviewed various manufacturing techniques for textile-based antennas. Their work provides insights into the fabrication processes, materials, and challenges associated with integrating antennas into textile substrates.[17] introduced a novel textile-inspired microstrip antenna designed for wearable applications. Their design focuses on integrating antenna functionality into textile materials, offering comfort and flexibility for users.

[18] represented a developed a compact jeans textile antenna suitable for wireless broadband applications. The antenna's design emphasizes miniaturization and integration into everyday clothing items, facilitating seamless connectivity. There is a scope of improving gain and presence of surface current can be optimised, which may disrupt the performance [19] shows circuit modeling and analysis of wearable antennas to understand the effects of bending. The study aids in designing antennas that maintain performance under various physical deformations. The paper lacks the comprehensive details on bending effects. There is limited data on how bending alters the dielectric characteristics of flexible substrates

[20] presented a compact flexible wearable loop antenna designed for enhanced performance in Wireless Body Area Networks (WBAN). Their design operates across multiple frequency bands, ensuring efficient communication within the ISM band. There is no inclusion of experimental SAR

analysis or human phantom testing. Safety impact of antenna radiation on the human body remains unverified and No prototype fabrication, bending tests on real clothing, or measurement in practical environments (like on-body tests) are presented.

[21] provided a comprehensive review on the design, analysis, and applications of wearable antennas. Their work encompasses various aspects, including materials, designs, and practical implementations in wearable devices. The effects of dynamic body movements on antenna performance need to be tested also selection of material is a challenge. [22] discusses new advances in antenna design for wearable devices, focusing on the use of nanomaterial. It highlights the potential of nanomaterial in enhancing antenna performance while maintaining flexibility and comfort. Antennas which are being used for the design of devices are designed by modifying patch shape in different configurations like patch, slotted patch loop, edge slot etc. Proposed work shows lower conductivity vs. copper. It lacks Stability under human body loading. The designed work is complex because of multi-band / multi-mode requirements.

[23] shows Designed a 4×4 MIMO antenna for smart eyewear covering Wi-Fi 5G/6E bands with high isolation and compact structure. No analysis of SAR, real-world bending/wear conditions, or durability in long-term use presented. [24] proposes a transparent 2.45 GHz antenna for smart glasses to support wearable IoT. Proposed work is limited to a single band, with no wideband/multiband support or performance validation under deformation. [25] covers the details about a 5G antenna with hemispherical coverage for AR glasses. The work presented lacks flexibility assessment and integration with compact wearable platforms.

Design, fabrication and testing of a frequency-reconfigurable patch antenna for Wi-Fi and 5G is explained in [26]. In paper reconfigurability is achieved, but at the cost of increased complexity and larger size. [27] reviews textile-based flexible and printable sensors for wearable applications. The paper highlights major challenges in durability, washability, and consistent electrical performance [28] proposes 3D human pose estimation using IR-UWB radar with transformers for through-wall sensing. The proposed work is not optimized for wearable integration; focuses more on sensing than compact antenna design. In [29] a wearable IoT-optimized textile antenna with low SAR in three bands was developed. In the proposed work SAR was minimized, but mechanical durability and bending effects are not fully addressed.

In [30] dielectric properties of fabrics for use as antenna substrates was measured. No actual antenna integration or performance validation with human body coupling was presented.

[33] presents a flexible Bluetooth/Wi-Fi antenna for wearable use, where the performance under body proximity and SAR compliance was not studied.

[34] proposed a dual-band 6×6 MIMO antenna for glasses, compatible with Wi-Fi 6E/7. The problem with Large MIMO arrays is they may suffer from size, power consumption, and integration constraints in eyewear. A dual-band glasses-integrated antenna for 5G and Wi-Fi, is designed and explained in [35]. The work presents limited analysis on flexibility, SAR, and environmental durability.

[36] proposed sub-6 GHz 4G/5G conformal glasses antennas. The work is focused on conformality, but ignores long-term wearability and bending reliability.

[37] presented a comprehensive review of flexible sub-6 GHz 5G antennas. The paper identifies research gaps in fabrication, integration with textiles, and maintaining stable performance.

A spectacles antenna supporting Bluetooth, Wi-Fi, and Wi-Max for IoT is designed in [38]. The work supports multiple bands but no experimental SAR analysis or user comfort evaluation is provided.

[39] gives a review of design, materials, and fabrication of flexible wearable antennas for WBAN and healthcare. It lacks the detail of reliable methods to balance SAR reduction with antenna efficiency under bending/deformation and limited progress in scalable, low-cost fabrication. [40] explains various flexible/wearable antennas for biomedical use, emphasizing SAR, gain, and bandwidth optimization. There is a need for biocompatible, lightweight, and stretchable materials that maintain stable performance under real-life bending and environmental conditions

To understand the basics of modal analysis [31]and [32] was referred to. [32] presents the modal analysis of the triple frequency band notch UWB monopole antenna. [31] proposed the design of a triple-band notch UWB antenna using C-shaped slots.

Most works focus on band coverage, compactness, and reconfigurability, but common gaps remain in SAR validation, real-world testing (bending, wearing, environment), durability, and integration into practical wearable platforms. The integration of antennas into wireless systems presents unique

challenges including limited space, body interference, and the need for high-speed data communication. Literature reveals significant progress in microstrip patch antennas, flexible substrates. However, gaps exist in standardizing antenna designs that are robust against human body effects and capable of supporting efficient communication. This study addresses these challenges through targeted analysis and design. Sample Images of the previously designed antenna for the devices[8] & [11] shown in Fig 4.2. The significance of this study lies in creating an antenna that balances bandwidth, radiation efficiency, flexibility, and safety key for next-generation body-worn wireless devices. Fig 4.3 represents use cases of Human Body-mounted Antenna.

a)Single Loop Antenna b) AR-conformal Antenna c) Transparent Antenna

Fig 4.2. Sample Images of the Existing Wearable Antenna[8],[11]

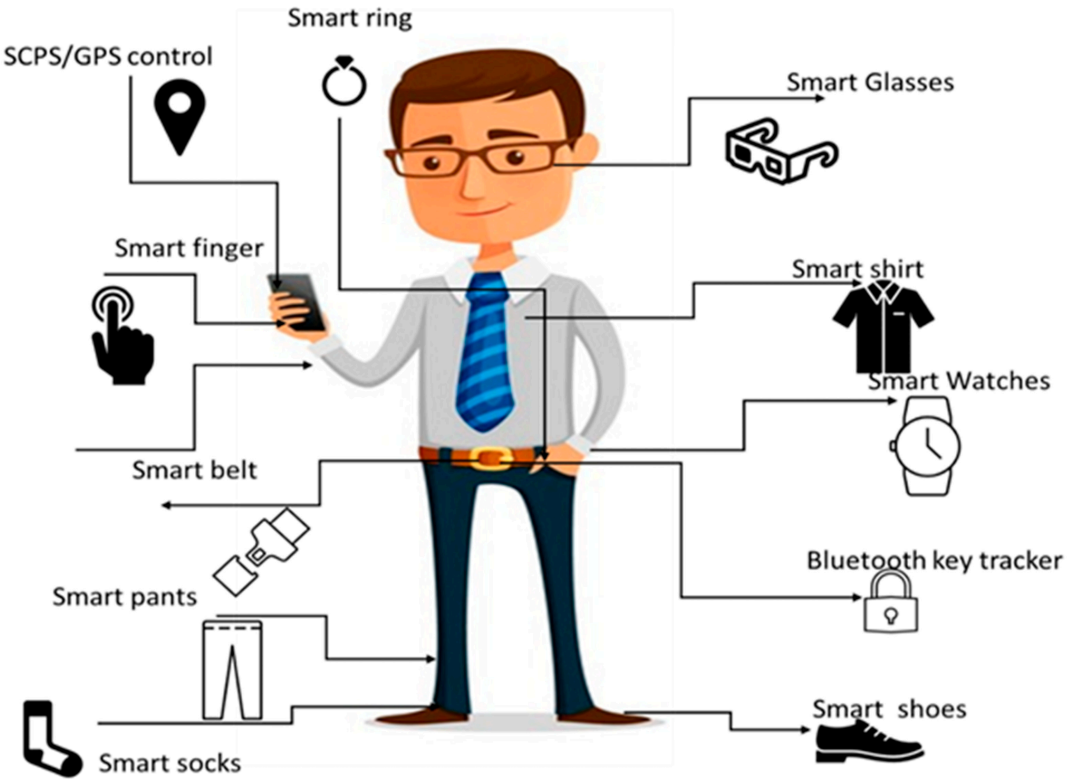

Fig 4.3. Use cases of Human Body-mounted Antenna [39]

With the understanding of literature a summary of 5W and 1H for few Wearable Antennas in Wireless Applications can be deduced, which is given as below,

Table 4.1 5W and 1H Understanding

Ref. No.	Name of the Antenna (What)	Publication details (Where)	Authors (Who)	Year of Publication (When)	Work Done/Key Findings (Why & How)	Gaps Identified
[6]	**Patch** (mm-Wave Wearable Antenna for Interaction with VR Devices)	Journal IEEE Antennas and Propagation	Haksun Son et al.	2024	● low loss tangent polyester fabric to minimize ● dielectric losses and a smooth coating to reduce losses ● due to rough surfaces 3.9mm in height and 8.8mm in width	few aspects like bandwidth can be dealt with to improve it from 0.1GHz to some effective increased value
[7]	**Distributed Mono-Pole & Patch** (Wearable Antennas for Virtual Reality Cross-Body Links)	Journal IEEE Antennas and Propagation	W. Su, P. V. Prasannakumar, Y. Li, G. Ye and J. Zhu	2023	● DM and Patch Antenna Dimensions ● size of 8.6 mm x 8.6 mm ● 13 mm x 13 mm ground plane ● Dielectric properties of body tissues were studied	The work represented here includes probe feeding that can be replaced with strip feed or aperture feed to avoid damage.Grounding can be improvised to avoid loss due to reflection
[8]	**Transparent** (Window-type and AR Glass-type Transparent Antenna Systems for B5G/6G)	Journal article IEEE Open Journal of Antennas and Propagation	S. -H. Park, et. al	2023	● 90 % optical transmission with a mm-sized electrode in a meshed structure ● Wide Aperture gives good SNR ● Window type Antenna (patch loop type) transmitter and AR Glass Transparent Antenna (Receiver)	The work only highlights the applications like transreceiving no focus on the antenna design parameters like substrate material, gain which are the key factors while designing for an ARVR device
[9]	**Edge slot** (Optically Transparent Antenna for Smart Glasses)	Journal article IEEE Open Journal of Antenna and Propagation	Y. Morimoto , et. al	2023	● Simulation and analysis of different antenna designs, including dipole, Microstrip, slot, and edge slot antennas.	Casing of the antenna can be compared for the enclosure loss reduction below 25%. efficiency can be improved further by modifying the layering stack.

Ref. No.	Name of Antenna (What)	Publication details (Where)	Authors (Who)	Year of Publication (When)	Work Done/Key Findings (Why & How)	Gaps Identified
[10]	**Microstrip U slot** (Pantoenna: Mouth Pose Estimation for VR/AR Headsets Using Low-Profile Antenna and Impedance Characteristic Sensing	Research article ACM Digital Library	Kim, Daehwa et. al,	2023	● Antenna designed to do mouth pose estimation	Substrate material is a Lossy copper material. We have a scope of exploring other flexible materials
[11]	**Single Loop and Conformal antenna** Augmenting Augmented Reality with Non-Line-of-Sight Perception	Research article Symposium on Networked Systems Design and Implementa-tion	Tara Borousha ki et. al	2023	● its gain degraded by 3 dB and frequency ● detuned by 120MHz when placed on the headset visor and worn by the user	Current literature covers very poor negative gain values. There is a scope for size reduction and on-body testing for the performance improvement with positive gain value

5. National Status

In India, research on wearable antennas is at a nascent stage, with emerging projects in academic institutions such as IITs and IISc. While some progress has been made in flexible antenna design and simulation, practical integration into commercial platforms is limited. References [13-15], [17-20], [33], [38], are few that present the work done in the field of antennas for wearable devices.

6. International Status

Globally, antenna design is an active area of research in wireless communication due to demanding end users. Companies like Meta, Microsoft, and Apple invest in advanced antenna systems for next-gen headsets and other wireless applications. International academia is exploring metamaterial-based antennas, beamforming arrays, and low-SAR solutions using electromagnetic simulation tools like HFSS, CST, and COMSOL. The majority of the references present the

detailed work done in the field of wearable antennas in devices to list a few mentioned in [6-11], [21-29], [34-37].

7. Study Hypotheses

To design and evaluate a novel human body mounted wideband antenna employing flexible substrate and conductive material for wireless applications, with a focus on minimizing interaction with the human body and ensuring decent performance under off-body and on-body scenarios.

8. Study Rationale

With the advancement of 5G and beyond 5G technologies are becoming more integrated into daily life. For a seamless connectivity antenna plays a crucial role. Hence the need for compact and efficient antennas is critical. This study provides a foundation for designing antennas that meet the demands of future wireless systems in terms of size, conformability, frequency, coverage, and user safety.

9. Research Methodology

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As per the proposed objectives the following methodology will be adopted:

1. As per design specification selection of suitable shape and material.
2. Theoretical design of antenna and its simulation using suitable softwares such as HFSS CST Microwave Studio, MatLab.
3. Off-body and on-body Simulation of Antenna for SAR rating.
4. Performance evaluation of proposed antenna on human body under bended and unbended scenarios.
5. Prototype fabrication and testing of antenna using VNA in an anechoic chamber & open environment for parameters such as gain, impedance bandwidth (VSWR $\leq$ 2), radiation pattern, polarisation, efficiency and trans-receiving capacity.
6. If there are some tolerances during fabrication, refabrication of the prototype antenna has to be done carefully to meet the requirements of wireless communication. Repeat the measurement steps as mentioned in step 5.

The flowchart of the method sequence to be adapted for the design of the proposed antenna is depicted in Fig 9.1.

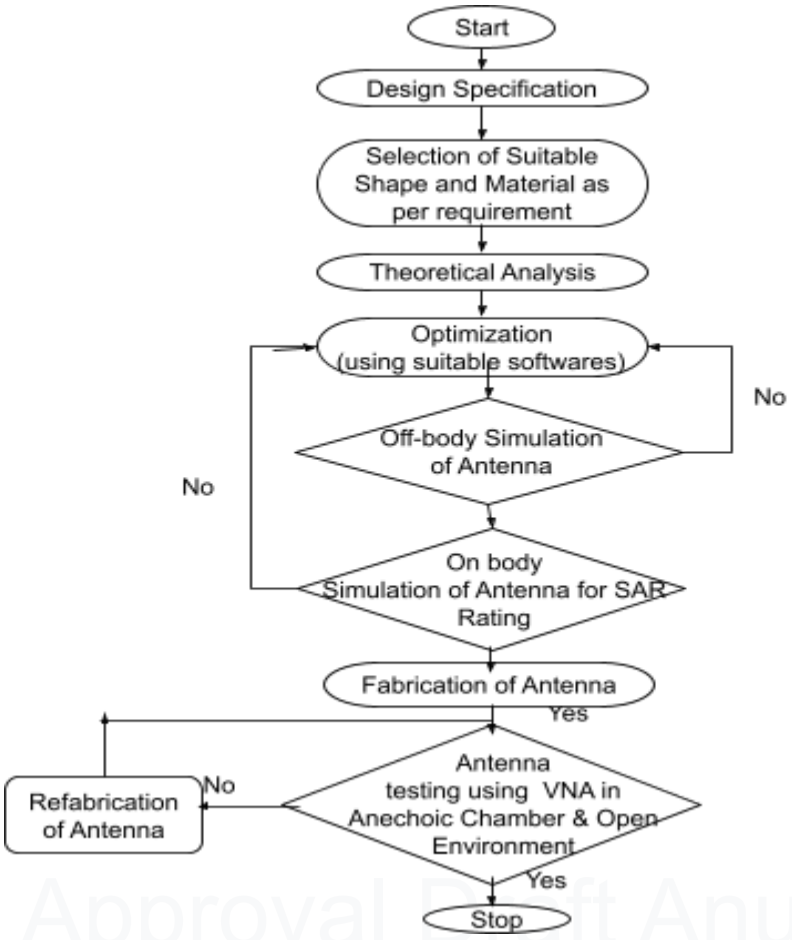

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Fig 9.1. Flow chart for sequence of the design steps.

10. Statistical Plan

Table 10.1 Statistical Plan

Sr. No.	Task to be completed	Plan and Timeline					
		Year 1 Phase 1	Year 1 Phase 2	Year 2 Phase 1	Year 2 Phase 2	Year 3 Phase 1	Year 3 Phase 2
1	Review of literature						
2	Simulation of existing designs of Antenna using HFSS						
3	Writing and Presenting Research Paper in International Conference.						
4	Proposed Method Design and Simulation						
5	Testing and Validation						
6	Journal Publication Thesis Writing						

11. Limitations of the Study

a. Limited access to advanced fabrication for mmWave antennas.
b. Variability due to human body interactions.
c. Limited duration for longitudinal performance studies in real-world use cases.

12. Expected Outcomes of Study

The proposed antenna designed should have the following characteristics

1. **Conformability**:Prototype antenna has to be conformal as per requirement of shape and it should be lightweight

2. **Ergonomic Integration**: Non-obtrusive placement—antenna does not interfere with optics, sensors, or user comfort.

3. **Sufficient Impedance bandwidth** for fast wireless communication.

4. **Wideband performance characteristics** of the proposed antenna should be suitable under bended and unbended conditions due to shift in resonant frequencies because of alteration in dimensions.

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5. **Sufficient gain** as per requirement to maintain strong signal even with user movement and partial obstructions.

6. **SAR compliance and safety** : Specific Absorption Rate (SAR) must comply with regulatory standards (e.g., FCC, CE). and minimized RF exposure to the user's head and body.

7. **Adequate signal coverage** between transceiver antennas as per their placement for seamless connectivity.

8. **Mechanical and Environmental Resilience**

- Performance must remain stable despite sweat, heat, and mechanical stress.
- Durable under various usage environments (indoor, outdoor, active movement).

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TOPIC APPROVAL SEMINAR ATTENDANCE

Research Scholars Attendance

Department:Electronics and Telecommunication Engineering **Date:22/08/2025**

SR	Name of the Research Scholar	Signature
1	Anupama Santosh Chaurasia	

Name and Signature of the Supervisor
Dr. Jayashree Khanapuri

Name and Signature of the Subject Expert (s): 1. Dr. Amit A. Deshmukh 22/08/25

2. Dr Milind Nemade

22/08/2025
PhD Coordinator
Dr. Hariram Chavan

Head of The Department
Dr. Jayashree Khanapuri

25/08/25
Principal
Dr. Vivek Sunnapwar

K.J. Somaiya Institute of Technology Sion Mumbai 400 022.

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K J Somaiya Institute of Technology
Sion (E), Mumbai - 400 022

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Sion East Mumbai Maharashtra 400022

Research Advisory Committee Report on Topic Approval Seminar

Department: Electronics and Telecommunication Engineering **Date: 22/08/2025**

1.	Name of the Candidate	ANUPAMA SANTOSH CHAURASIA		
2.	Admission/ Registration No:	2220240799		
3.	Course Work Details	**Course Title**	**Credits**	**Grade Obtained**
		1) Research Methodology	6	O
		2) Electromagnetic Waves in Guided and Wireless Media	6	B
		3) Seminar	4	B
		4) Research & Publication Ethics (RPE)	2	O
		SPI: 8.89		
		Whether the candidate has successfully completed the course work, which is a prerequisite for registering him/her for the PhD Program at the University of Mumbai.		Yes
4.	Proposed Research Title	Design a novel human body-mounted wideband antenna employing flexible material for wireless communication		

5.	Literature Review	Satisfactory / ~~Unsatisfactory~~	Satisfactory
6.	Novelty in Proposed Research	Satisfactory / ~~Unsatisfactory~~	Satisfactory
7.	Presentation of Research Work	Satisfactory / ~~Unsatisfactory~~	Satisfactory
8.	Overall Recommendation for the Topic Approval	Recommended / ~~Not Recommended~~	Recommended
9.	Other Comments (If any)		

Research Advisory Committee (Name and Signature)	
Chairperson	Dr. Vivek Sunnapwar
Research Supervisor	Dr. Jayashree Khanapuri
Internal Subject Expert 1	Dr Milind Nemade
External Subject Expert 2	Dr. Amit A. Deshmukh

Dr Hari Vanjavan
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Dr Jayshree Khanapuri
Head of The Department

Dr Vivek Sunnapwar
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K. J. Somaiya Institute of Technology Sion Mumbai 400 022.

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